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HIGH ENERGY LASER ON THE JOINT STRIKE FIGHTER

A REALITY IN 2025?

by

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Contents

DISCLAIMER II

INTRODUCTION 1

SCOPE OF ISSUES RELATED TO HEL INSTALLATION ON THE JSF 4
- Assumptions 5
  - HEL Specifications 5
  - LSF HEL Weight, Volume, Power, and Cooling System Budget 6

HIGH ENERGY LASERS 7
- Survey of HEL Technologies 7
- Technical Maturity and Potential of High-Energy SSLs 8
  - Metrics for Evaluating SSLs 8
- Bulk SSLs 10
  - Trends 10
- Fiber SSLs 11
  - Trends 11
  - Challenges 12
- SSL Technology Forecast Consensus 14

POWER GENERATION 15
  - LSF Power Requirements 15
  - LSF Power Generation Proposals 15
  - The Future of Airborne Power Generation 17
  - Power Generation Technology Outlook Consensus 17

THERMAL MANAGEMENT 19
  - Scope of LSF Thermal Management Problem 19
  - SSL Thermal Management Issues 20
  - Other Thermal Management Considerations 21
  - Thermal Management Technology Outlook Consensus 21

LASER BEAM CONTROL 23
  - Laser Beam Control Components 23
  - Lasers and the Atmosphere 24
  - Adaptive Optics and Atmospheric Turbulence Correction 24
  - Active Flow Control 25

Beam Control and Aero-Optics Technology Outlook Consensus.........................28

PROGRAMMATICS...30
HEL and Associated Subsystems Programs...30
Time...32
Funding...32

CONCLUSION AND FURTHER QUESTIONS FOR CONSIDERATION 34

LASER FUNDAMENTALS 38

BIBLIOGRAPHY...39

Tables

Table 1. Issues Pertaining to HEL Installation on the JSF 4

Table 2. LSF Weight, Volume, Power, Cooling System Budget 6

Table 3. Issues Pertaining to HEL Installation on the JSF 30

Table 4. AFRL FLTC Products Enabling LSF Development...31

Abstract

High energy lasers (HEL) promise speed-of-light engagement, precision effects, and low collateral damage. These characteristics along with a nearly unlimited magazine make HELs attractive for installation on a tactical platform. This paper will consider whether a HEL equipped F-35 Joint Strike Fighter (JSF) could be fielded in 2025.

To answer this question, three topics will be explored. First, will HELs be sufficiently technically mature to permit installation on a fighter platform? Second, will the key supporting systems, to include power generation and storage, thermal management, and beam conditioning and control, be sufficiently technically mature for installation on a fighter platform? Next, will maturity of the key supporting systems occur in time to support a program to integrate a HEL on the JSF? Finally, are the development schedules and funding for the HEL, key supporting systems, and the JSF synchronized to support a 2025 fielding?

The research methodology includes a review of current efforts in each of the technology areas mentioned previously. Additionally, interviews with key personnel involved with the JSF program are used to understand the challenges associated with integrating the aforementioned technologies on the JSF.

The research concludes that the technical maturity of HELs and their supporting systems will be sufficiently advanced to permit fielding a HEL equipped JSF in 2025. The key issue that may prevent this from occurring is a lack of dedicated funding, both for development of the enabling technologies and also for the HEL integration effort on the JSF. The author closes the paper by exploring the rationale for installing a HEL on the JSF and considering whether the

USAF's proposed long range strike vehicle would be a better candidate than the JSF for HEL integration.

Chapter 1

Introduction

"You know, I have one simple request. And that is to have sharks with frickin' laser beams attached to their heads!" Dr. Evil

High energy lasers (HEL) promise speed-of-light engagement, precision effects, and low collateral damage. These characteristics along with a nearly unlimited magazine make HELs attractive for installation on a tactical platform and will likely offer a unique capability to the warfighter. While HELs are not a replacement for guns, air-to-air missiles, or bombs, they do provide effects and capabilities that the aforementioned weapons do not and cannot provide. This paper will consider whether technical maturity of HELs and necessary supporting systems will permit fielding of a HEL equipped F-35 Joint Strike Fighter (JSF) in the 2025 timeframe. The choice of a 2025 fielding date, while arbitrary, is the time horizon specified for the 2006-2007 Air War College Horizons 21 study group.

To answer this question, three topics will be explored. First, will HELs be sufficiently technically mature to permit installation on a fighter platform? Second, will the key supporting systems, to include power generation and storage, thermal management, and beam conditioning and control, be sufficiently technically mature for installation on a fighter platform? Next, will maturity of the key supporting systems occur in time to support a program to integrate a HEL on the JSF? Finally, are the development schedules and funding for the HEL, key supporting

systems, and the JSF synchronized to support a 2025 fielding? Lockheed Martin refers to the HEL variant of the JSF as the Laser Strike Fighter (LSF); for brevity, this paper will as well.

To manage the scope of this paper, some issues associated with HEL installation on a JSF will not be considered. This should not be taken to mean these issues are not important or perhaps even critical to the question of whether the USAF should pursue the LSF. Some of these issues include legal, ethical, and policy decisions that take into account the unique effects that HELs can have on combatants and non-combatants; these unique effects include blinding and thermal effects on skin and clothing. Furthermore, HEL effects can extend far beyond the intended target in the event of a miss. System design requirements and employment doctrine to mitigate fratricide potential and potential inadvertent exposure of non-combatants are key issues for HEL employment that will not be considered here.

The research methodology relies upon expert opinions of those developing HELs, key supporting systems, and HEL integration concepts for the JSF. The experts include HEL research scientists at Kirtland AFB, the Air Force Research Lab (AFRL), and the Air Force Institute of Technology (AFIT). Systems engineers at Lockheed Martin provided information on system integration issues. Lastly, AFRL, the Joint Technology Office (JTO), the JSF System Program Office (SPO), and Air Combat Command (ACC) furnished data on the timeline and feasibility for a LSF program.

Before moving on to the particular technologies in question, a point must be made regarding critical evaluation of HEL capabilities and limitations. It is important for DoD decision-makers to carefully separate fact from fiction when considering the capabilities offered by Directed Energy (DE). Dr. Doug Beason, in his book *The E-Bomb*, makes the following statement about air-to-air combat to build the case for the revolutionary capabilities offered by HELs.

> However, instead of using an air-to-air missile, suppose you blast the jet with a laser weapon. Instead of minutes, it takes just 1/1000 of a second for the beam to reach the enemy jet 300 kilometers away. In that length of time the jet would have traveled a third of a meter, or about a foot, leaving no time for an evasive maneuver.[1]

What is wrong with this statement? It is factually correct, but leaves unstated several critical assumptions. The context of this statement is in a vignette describing a fighter versus fighter engagement. HEL power levels on a fighter will likely be on the order of kilowatts, not megawatts. Kilowatt class lasers will not have a lethal range anywhere near 300 kilometers; 100 kW laser lethal effects will be limited to well under 100 kilometers, particularly if the desired effect is melting versus blinding. More importantly, while it is true the enemy jet will only move about a foot in that amount of time, this statement ignores the fact that the HEL beam will have to dwell on a specific target aimpoint for approximately 5-10 seconds in order to achieve a lethal effect. Could evasive maneuvers be accomplished in that amount of time, and if so, would they be effective? The point is this; HEL effects are different than kinetic effects produced by bullets or missiles. A thorough understanding of laser principles and effects is necessary to allow decision makers to challenge the underlying and often unspoken assumptions justifying HEL capabilities.

HELs have characteristics that can provide capabilities currently unavailable to warfighters; they will compliment, but not replace, current kinetic weapons. We will next examine the range of issues associated with development and integration of a HEL on the JSF.

Chapter 2

Scope of Issues Related to HEL Installation on the JSF

There are many issues that must be considered when evaluating the probability of HEL installation on the JSF in the 2025 timeframe; Table 1. is comprehensive but not necessarily all inclusive. A 2004 Futures Study conducted by the Science Applications International Corporation (SAIC) identified power sources, Solid State Laser (SSL) power output, thermal management, and laser energy propagation and stability in the atmosphere as being the most critical issues before directed energy weapons could be adapted for airborne tactical military applications.[2]

Table 1. Issues Pertaining to HEL Installation on the JSF

Technology and Programmatics	Effectiveness Limiting
HEL Technical Maturity	HEL Employment Policy
Power Generation	HEL Effects Characterization
Power Storage	HEL Employment Doctrine
Thermal Management	Weather
Adaptive Optics / Active Flow Control	Battlefield Obscurants
LSF Cost and Schedule	

Division into these two categories is arbitrary by the author for the purposes of controlling the scope of the paper. The second category, **Effectiveness Limiting**, includes those areas that may affect but not prevent the effective use of a HEL and will not be considered in this paper. Interviews with the JTO and Lockheed Martin have identified the issues listed under the **Technology and Programmatics** header as the most difficult to solve both technically and

programmatically; these are the issues this paper will specifically address. Assumptions regarding USAF requirements for baseline LSF HEL power levels will be discussed next.

Assumptions

HEL Specifications

On-axis intensity of a laser beam is directly related to laser output power and inversely related to the square of the range to the target.[3] Lasers with power levels around 25 kW can be used in a defensive mode, such as negating ground-to-air missiles. Lasers with 50 kW begin to offer offensive air-to-air capabilities. To provide lethal air-to-ground effects, at least 100 kW of output power is needed.[4]

This paper assumes the USAF would initiate a program to integrate a HEL on a platform like the JSF only if it offered both air-to-air and air-ground capabilities. Therefore, we will assume a baseline requirement for a 100 kW laser on the JSF and consider the demands that a laser of that power would make on power generation and energy storage capacity, thermal management capacity, beam control, and finally the programmatics of integrating that class of HEL on the JSF.

LSF HEL Weight, Volume, Power, and Cooling System Budget[5]

Table 2. lists the Lockheed Martin planning assumptions for the LSF. These assumptions will be revisited throughout this paper to ensure proposed technical solutions fit within Lockheed's weight, volume, power, and cooling budget allocations.

Table 2. LSF Weight, Volume, Power, Cooling System Budget

Weight	≤ 5500 lbs for HEL, power, cooling, and aircraft mods
Volume	~ 95 ft^3
HEL Efficiency	10% wall plug efficiency
Input power required	1.2 MW
Thermal load to be dissipated	1.1 MW

Thus far we have listed the technology and programmatic issues that will be the focus of the remainder of this paper and have also listed some assumptions related to capability and engineering constraints that the LSF will need to meet. The next five chapters will examine the technology and programmatic issues in more detail with a goal of arriving at a reasoned assessment of the likelihood of the LSF becoming a reality in the 2025 timeframe.

Chapter 3

High Energy Lasers

Survey of HEL Technologies

The history of military laser development dates back to the 1960s, with the first practical demonstrations of HEL capability occurring in the early 1980s with the Airborne Laser Laboratory (ALL) program. Current DoD chemical HEL programs include the Airborne Laser (ABL), Advanced Tactical Laser (ATL) and the Tactical High Energy Laser (THEL). Of these programs, only the ABL is megawatt-class.[6] Currently, chemical lasers are the only laser technology capable of generating large amounts of power. Unfortunately, chemical lasers do not lend themselves to use on the LSF. Carriage of hazardous chemicals, the large size of the chemical storage tanks, and the difficulty of dealing with the combustion byproducts will relegate chemical lasers to larger aircraft like the ABL's 747 and the ATL's C-130 for the foreseeable future.[7] The other limitation of a chemical laser is a limited magazine. Until in-flight regeneration of lasing chemicals is possible, all airborne chemical lasers will have their employment duration limited by the amount of chemicals they can carry on board. A deep or unlimited magazine should be a key performance parameter for the LSF, particularly for executing the counter cruise missile mission, and is an inherent feature of the next laser technology we will examine.

There is another technology for generating a laser beam that is more suited to installation on the JSF, and that is the SSL.[8] SSLs are ubiquitous in modern life and on the battlefield. Low-power SSLs are found in CD players, laser pointers, and power tools and on the battlefield in laser rangefinders and laser designators. The technical challenge lies in the ability to scale SSL technologies to generate the power needed to provide lethal effects.

Technical Maturity and Potential of High-Energy SSLs

There are two major categories of SSLs, bulk and fiber, and rapid technological progress is being made in both categories. Fiber SSLs currently seem to have the most promise for the LSF, but it is still too early to say which technology will be most mature in 2025. Appendix A provides background information on laser technologies for the interested reader. In order to properly evaluate and compare competing lasers and laser technologies, some understanding of laser metrics is necessary.

Metrics for Evaluating SSLs

Beam quality, efficiency, and SSL weight are the most important metrics used when evaluating and comparing SSLs. Comparing the weight of competing SSL systems is a simple task and no further explanation is necessary. However, some care must be taken when comparing beam quality and efficiency, as a few different measurement systems exist for both. It can be difficult to directly compare two lasers, particularly if they use different technologies to generate their beams. This is because some beam quality metrics are more suited to measuring one technology versus another.

Beam quality can be measured in several different ways. The three most common methods are M^2, Strehl Ratio, and Power in the Bucket (PIB). The mathematics behind these methods is

beyond the scope of this paper. What is important to understand is that each of these methods measures a particular aspect of the laser beam. Because of this, the metrics resulting from these different measurement methods are often not directly comparable.[9] One of the main causes of this problem is defining the laser beam itself. The intensity of laser radiation does not decrease linearly from the center of the beam. The challenge with defining the beam then is what radius from the center of the beam should be specified to define the output of the laser? Some laser power measurement methodologies specify a radius at which the power output has fallen to some percentage of the level measured at the center of the beam. However, there are other potential ways to specify the radius as well. In general, one cannot draw a circle around a laser beam and have all the power of the beam reside inside the circle, and none of the power outside the circle due to the non-linear power drop-off from the center of the beam. Therefore, the issue becomes how big do you draw the circle? This difficulty is why AFRL/DE scientists advocate the PIB method. "PIB is the only beam quality reference that includes a measure of the "design adequacy"—how efficiently one can deliver power to the target."[10] At a radius of zero around the laser beam bore line, PIB equals zero. At a radius of infinity, PIB equals one. As the radius is increased from zero, a PIB measurement can be derived from any arbitrary radius, with PIB being the fraction of total energy being deposited at the specified radius. Unfortunately, while chemical lasers are known for their inherent good beam quality, SSLs are not.[11] Thermal effects, particularly in bulk SSLs, are a major contributor to beam quality degradation due to the thermally induced changes of the refractive index of the laser's gain material.[12] The inherent thermal management benefits of fiber SSLs due to their large surface area may help overcome adverse thermal effects issues in bulk SSLs.[13]

SSL efficiency can also be measured in different ways, depending on what aspect of laser operation is being focused on. Wall-plug efficiency will be the primary measure of efficiency used throughout this paper. Wall-plug efficiency is simply the ratio of power output divided by electrical power input into the laser. As stated in Table 1., Lockheed Martin is planning for a SSL with 10% wall-plug efficiency. However, wall-plug efficiencies in the range of 30% have already been achieved.[14] It is important to note that 30% efficiencies have not been achieved in high power, high beam quality lasers. Existing high power SSL programs such as JHPSSL and the DARPA HELLADS programs are projecting efficiencies near 10%.[15]

PIB can be used to compare the relative fractional power outputs at a given radius from the central point of the laser spot for all lasers, chemical or solid-state. In contrast, wall-plug efficiency is only applicable to solid-state lasers. Now that we have some fundamental understanding of how laser power and efficiency are defined and measured, we will examine the two basic SSL laser technologies currently being explored, bulk and solid-state. Fundamentals of bulk and fiber SSL design are discussed in Appendix A.

Bulk SSLs

Trends

The most current evaluation of bulk SSL technologies was released 11 October 2006 by AFRL/DE. Three ongoing bulk SSL programs were examined in this evaluation: Northrop Grumman Space Technologies Master Oscillator Power Amplifier (MOPA) Chain; General Atomics High-Energy Liquid Laser Area Defense System; and Textron's ThinZag™. Each program is following a distinct technological path towards the goal of demonstrating a 100 kW

class bulk SSL laser capability. AFRL/DE's assessment is each program is on track to demonstrate 100 kW output around 2008.

AFRL/DE identified several issues that would impact the military utility of high-power SSLs. Those issues include efficiency, volume, weight, reliability, maintainability, supportability, effectiveness, thermal management, electrical power generation, and electrical energy storage. Key issues to the integration of a SSL on the JSF include the latter three. Electrical power generation, electrical energy storage, and thermal management are the topics of Chapters 4 and 5. These topics and AFRL/DE's assessment of the technological maturity of these areas will be discussed in those chapters.

Fiber SSLs

Trends

There are several clear trends observable within the fiber SSL technology area: power output per fiber is increasing, methods to coherently phase individual fibers are being demonstrated, and the commercial sector's interest in improving the properties of optical fibers all point to the likely achievement of 100 kW power output well before 2025.

An April 2006 report from AFRL/DE describes the dramatic advances taking place in fiber SSL power output. IPG Photonics went from commercial production of a 100 W fiber SSL to a 20 kW fiber SSL, over two orders of magnitude improvement, in only five years. It should be noted that the output of IPG's 20kW fiber laser was incoherent.[16] Overall, fiber laser power output is growing exponentially, but there are physics limitations to the maximum output power of fiber lasers that lend themselves to bundling in a phase-matched array. That physics limitation appears to be approximately 500 W per fiber.[17]

Caution should be used when using past progress in SSL power output to project future progress in SSL power output. SAIC in 2004 envisioned a SSL capability on the JSF capable of providing air-to-air and self-defense effects in a "7+" year timeframe.[18] SAIC went on to say, "Though it is tempting to speculate on the timing of Directed Energy Weapons (DEW) developments, some felt that the level of uncertainty is high enough that specific technical goalposts may be premature, especially for the second-generation systems focusing on electric lasers."[19] Clearly we will not have a SSL on the JSF in 2011, but this SAIC projection was mentioned to provide some bounding on the timeframe in which SSLs could be ready for the JSF, as well as to induce some healthy skepticism in the reader as to the reliability of SSL technical maturity projections.

Challenges

AFRL researchers at Kirtland AFB believe fiber SSLs will be the SSL technology most suitable for integration on a fighter-sized platform. Fiber SSLs are inherently rugged, likely to be scalable, and particularly well suited for effective thermal management compared to their bulk brethren.[20] However, there is still a lot of development occurring in bulk and fiber SSLs and the jury is still out on which technology will be most suitable for use on the LSF.

The scaling problem is the key engineering challenge for fiber SSLs. There are two key contributors to total fiber SSL power output. The first contributor is improving the power output of an individual fiber and the second is the ability to match the phase of a bundle of individual fibers so the combined output is coherent. To illustrate, 100 W-class amplifiers exist today. By bundling 1,000 fibers together, one could achieve a power output of 100 kW. The more difficult engineering challenge of the two power contributors lies in matching the phases of the individual fibers to achieve a coherent output.[21]

What is the progress with respect to matching the phase of individual fibers to achieve a coherent output? This is a key research area within the overall fiber SSL effort, and several approaches are being used to solve the challenge. To date, all of these approaches are demonstrating the ability to phase-match fibers, albeit in low number's of fibers. The technical challenge lies with demonstrating the ability to phase match the hundreds or thousands of fibers needed to generate a kW class SSL.

Before describing the phase matching approaches, it is important to understand the dual nature of the problem of matching fiber laser output. Current fiber laser approaches use more than one amplifier to feed the individual fibers. The first requirement for a high quality beam is that the amplifiers must all be coherent with each other. Typically a single master oscillator is used to provide a reference signal to each of the amplifiers, thereby ensuring that each of the amplifier outputs is coherent with each other. The second challenge is to make sure the phases of the outputs of the individual fibers are matched. Differences in fiber lengths, temperatures, and/or refractive indices will affect the phase output of the individual fibers and therefore must be compensated for. Without phase compensation, the output of the fiber bundle may be coherent, but the resulting wavefront will be distorted, leading to power dissipation as the beam progresses towards the target.[22]

One of the fiber SSL phase matching approaches developed thus far uses a passive spatial filter. This passive method was successful in matching the phase of two unequal length fibers, and also compensating for phase changes due to mechanical distortion and temperature changes within the fibers.[23] There do seem to be limitations to the maximum number of fibers that can be passively phase-matched, so the passive method may not be suitable for combining large numbers of fibers needed for a 100 kW fiber SSL, which will likely be on the order of 200-250

individual fibers.[24] An alternative approach used by Northrop Grumman utilized active feedback to adjust the phase of the individual fibers. This approach successfully phase matched the output of four fibers. The Northrop Grumman team does not foresee a limitation to their ability to correct phase errors as more fibers are added to the output. It is interesting to note that this demonstration produced single fiber output of 155 watts. This means that just under 650 fibers would be needed to achieve 100 kW of total output power. Like the phase matching problem, Northrop Grumman researchers feel output power of individual fibers should be scalable as well.[25]

SSL Technology Forecast Consensus

Clearly, rapid progress is being made in both bulk and fiber SSL power output. Neither technology seems to be revealing any fundamentally limiting technical issues preventing scaling to kW class power levels. Many challenges remain to mature either technology for tactical platform integration, but the trend towards high power output from both technologies is clear.

Will a 100 kW class SSL, either bulk or fiber, be developed and mature enough for installation on the JSF by 2025? Discussions with Lockheed Martin, AFRL, and the JTO, and a survey of literature all indicate a 100 kW class SSL will be technologically ready in time to support a 2025 fielding of the LSF. If SSL maturity is not a limiting factor, will power generation prevent LSF fielding in 2025?

Chapter 4

Power Generation

LSF Power Requirements

As indicated earlier (Table 2), the JSF HEL will require approximately 1.2 MW of power to operate and cool, divided between the HEL itself (~771 kW) and the thermal management system (~200 kW). It is important to remember that this assumes a SSL wall-plug efficiency of 10%. AFRL/DE recently reported commercial fiber SSL wall-plug efficiency of 30%, with expectations that 40% could be achieved in the future.[26] SSL efficiency improvement would result in a marked reduction in both power generation and thermal management requirements. Thermal management will be covered in detail in Chapter 5. The question at hand is whether this power generation requirement can be met with current or projected power generation technology within the volume allocated in the LSF airframe. To meet the power generation requirements for tomorrow's directed energy weapons, AFRL's Propulsion Directorate is actively investigating the technologies needed to manufacture lightweight, high power generators and energy storage media.[27]

LSF Power Generation Proposals

The Joint Strike Fighter has a unique design feature that will simplify the power generation problem. The existing design for the **S**hort **T**ake**O**ff **V**ertical **L**and (STOVL) version of the JSF already has a mechanical shaft coming off the engine to power the lift fan. The LSF would use the lift fan shaft to rotate the generator(s) powering the HEL.[28] With approximately 27,000 shaft

horsepower of mechanical power available from the lift fan shaft, potential limitations with power generation will reside with the generators themselves.[29]

Generators exist today that are capable of producing the power required by the HEL; the problem is the weight of those generators. The LSF weight budget for the HEL generator is ~145 lbs. Presently, 1 MW class generators weigh around 1000 lbs, almost an order of magnitude higher weight than currently allocated for the LSF.[30] Powering a SSL will require development of lighter weight power generation technologies and careful assessments of the tradeoffs between power production capacity, weight, volume, and longevity in order to optimize the power generation system. AFRL/PRP has spent several years developing a lightweight, low duty cycle generator, and will soon be testing a 1 MW class generator that weighs approximately 200 lbs, close to the target weight for the LSF project.[31]

The first set of issues to consider are power production capacity, weight, and volume. The LSF SSL will have a duty cycle[32] under 100% because of thermal management issues. That means the power generation system does not need to be capable of continuously delivering the power required to operate the laser. A smaller generator could be employed, coupled with batteries and/or capacitors. The generator(s), batteries, and/or capacitors would operate the laser, then the generator would recharge the energy storage system during the laser down times. This concept has the advantage of requiring a smaller generator, albeit at the expense of the weight and volume of an energy storage system.[33] There is currently widespread government and industry interest in developing smaller and more efficient energy storage systems. Some examples of this interest include the auto industries pursuit of all electric or hybrid electric-gas vehicles, as well as the US Navy’s all-electric ship program. The combination of industry and government interest should ensure adequate research funding for this technology challenge.

The other key issue is longevity. More precisely, one challenge with reducing the weight of a generator while still producing the same power output is maintaining or increasing the amount of time the generator will function before it fails. Lockheed Martin engineers feel they could obtain generators capable of providing the required power while still fitting within the weight and volume allocation for the LSF today. Using existing generator technology to obtain higher power output would adversely impact generator longevity.[34].

The Future of Airborne Power Generation

Further development in power generation capacity and energy storage is needed before a reliable, lightweight, high power generation solution is available for the LSF. AFRL is exploring improved power generation and energy storage technologies as part of their Focused Long Term Challenges program. AFRL scientists P.N. Barnes et. al. released a paper in January 2005 that discussed recent research results from their work with high temperature superconducting (HTS) generators. HTS based generators promise dramatic improvements in power production and weight reduction compared to current generator technologies. They conclude that advances in HTS materials and corresponding improvements in generator design will enable development of megawatt class generators that are small, lightweight, and suitable for use on airborne platforms.[35]

Power Generation Technology Outlook Consensus

Is power generation for the LSF's SSL a showstopper? Again, the consensus of AFRL, JTO, and Lockheed Martin is no. Trade studies will certainly be required to determine the optimum combination of generator capacity and temporary storage capacity from batteries or capacitors, but there is little doubt that the technology for both power generation and energy storage will mature to the point of meeting the LSF SSL requirements. If there are limitations to

power generation capacity, they will more likely result in reduced firing times or duty cycles for the LSF SSL, not prevent its implementation entirely. It is also important to realize that modest gains in SSL efficiency will have a direct effect not only on power production requirements but thermal management as well. Obviously, improving SSL efficiency from 10% to 20%, a modest goal, will cut the power production and thermal management requirements in half. Generating sufficient electrical energy to power a 100kW SSL will result in a substantial amount of waste heat. Consequently, thermal management is another major issue that must be solved before the LSF can become a reality. The potential solutions for the thermal management problem are the topic of the next chapter.

Chapter 5

Thermal Management

Scope of LSF Thermal Management Problem

There are two main thermal management problems resulting from airborne use of a SSL. The first problem is removing waste heat from the SSL itself and the second is what to do with the SSL waste heat once it is extracted. An airborne platform has some unique weight, volume, and environmental constraints that place limits on the total amount of thermal energy that can be dissipated in a given amount of time. Dissipation of LSF SSL waste energy in real time is probably not achievable. The weight, volume, and power requirements for a system capable of performing that task would be prohibitively large for the LSF. Lockheed Martin engineers envision limiting HEL operation to a 33% duty cycle for the first 65 seconds followed by a period of minutes for cooling to make the thermal management problem easier to deal with in a reasonable amount of weight and volume.[36] A duty cycle under 100% could be a significant limitation if the HEL is being used in a defensive mode. However, the JSF datalink could allow cooperative targeting and employment within the flight. Therefore, a flight of three LSFs with a 33% duty cycle would still have an aggregate 100% duty cycle.

There are several cooling technologies currently available that are applicable to the HEL thermal management problem, including liquid, vapor, and phase change. Lockheed Martin engineers propose using a liquid to extract thermal energy from the HEL and then transport the

waste heat to a temporary energy storage tank. When the tank has reached its maximum thermal storage capacity, SSL operation would terminate. Next a vapor cycle system will extract the heat from the temporary storage tank and move it to the JSF's fuel system. Given this proposed design, what is the readiness of each of the cooling technologies?

Lockheed Martin engineers believe that existing single-phase liquid loop, phase-change thermal storage, and vapor cycle technologies are capable of handling the anticipated HEL thermal load. Key HEL parameters affected by improvements in cooling technologies will be strictly operational: higher duty-cycle, shorter periods of time needed to extract heat from the temporary storage tank, and lighter weights for components of the entire thermal management system, particularly the energy storage system.[37] As previously discussed, improvements in SSL efficiency will directly translate to reduced thermal management requirements.

Thermal management issues do not reside solely outside the SSL. Heat removal from the SSL lasing medium is a key issue, affecting not only survivability of the lasing medium itself but also directly affecting the quality of the SSL beam. Some of those SSL specific issues will be discussed next.

SSL Thermal Management Issues

High power SSL operation produces thermal energy that must be dissipated to prevent optical distortion, material failure of the lasing medium, or thermal damage to the associated support equipment. SSLs are inherently inefficient electronic devices, typically on the order of 10% wall-plug efficiency.[38] Therefore, a 100 kW laser will require approximately 1 MW of power input, and dissipation of a resultant 900 kW of waste heat. Thermal management of bulk SSLs is particularly difficult. Heat buildup in bulk laser gain media can induce beam distortions

and mechanical failure of the gain medium itself.[39] AFRL/DE describes thermal management of bulk high power SSLs as "a major problem and a fundamental limiting issue."[40]

Fiber SSLs have one key design advantage over their bulk SSL counterparts when it comes to thermal management. Fiber SSLs possess optical and physical properties that provide them with superior heat dissipation characteristics compared to bulk SSLs.[41] Even though uneven thermal gradients within a multi-fiber SSL induce phase changes between the individual fibers, the phase-matching systems required for a multi-fiber laser appear to be capable of correcting thermally induced phase shifts.

Other Thermal Management Considerations

Thermal management on an airborne platform, particularly a stealthy platform, must consider increases in the overall thermal signature of the platform. Dissipating thermal energy on a stealth platform has the potential to increase its vulnerability to detection or engagement by systems operating in the infrared region. While dissipating nearly 1 MW of energy may seem to imply an unacceptable increase in the overall thermal signature of the JSF, it is a relatively small portion of the overall thermal signature which primarily results from the engine.[42]

Thermal Management Technology Outlook Consensus

The thermal management advantages of fiber SSLs coupled with the rapid advances in fiber laser power output make it likely SSL thermal management will not be a limiting issue in integrating a SSL on the JSF. Lockheed Martin engineers feel the platform thermal management problem is solvable using current thermal management technology. Improvements in SSL efficiency, thermal management technologies, and advances in phase change materials used in thermal management systems will result in improvements in the LSF SSL duty cycle, firing duration, and recovery time.

Thus far we have examined bulk and fiber SSL technologies, power generation, and thermal management issues. None of these areas has produced an issue that is likely to prevent successful integration of a SSL on the LSF by 2025. The final and perhaps key engineering challenges to be explored are beam control and aero-optics. The next chapter will describe the functions of beam control and aero-optics for SSL employment and examine some of the challenges associated with these technologies.

Chapter 6

Laser Beam Control

Laser Beam Control Components

Laser beam control is used to maintain the quality and lethality of the laser beam from the time it exits the laser aperture until it impacts the target. There are three main components of laser beam control. The first is mitigating the effects of atmospheric distortions between the laser aperture and the target and is the purview of adaptive optics. The second component is mitigating the effects of airflow turbulence in the vicinity of the laser aperture and is managed by active flow control (AFC) and to some extent adaptive optics. The final component of laser beam control is maintaining a track on a specific point on the target. This part of the beam control problem is further divided into two sub-components. The first is the problem of controlling and minimizing jitter generated by the lasing platform. The other sub-component is the issue of selecting and maintaining an appropriate aimpoint on the target based on the particular characteristics and vulnerabilities of the target.

The intended mission for the HEL is also a major design consideration for the beam control system. If the HEL system is defensive in nature, then full coverage around the entire platform is desirable. Technically, this full coverage is referred to as a 4 π steradian employment envelope. Conversely, a front-quarter only limitation may be acceptable for offensive missions.[43] Certainly, the 4 π steradian case is the most technically stressing, and would require

apertures on the top and bottom of the platform. The current LSF concept features an aperture only on the bottom of the platform.

Lasers and the Atmosphere

Before examining the beam control issues, a word about the atmosphere itself is in order. Laser energy is subject to attenuation by a variety of substances present in the atmosphere. Those substances include invisible components like atmospheric gasses and water vapor, and visible components like clouds, fog, dust, and smoke. To some extent, laser designers can select an operating frequency optimized to negate the attenuation effects of atmospheric gases and water vapor, but visible moisture and obscurants cannot be corrected for and therefore will not be addressed in this paper. Neither bulk nor fiber SSLs are tunable to compensate for varying atmospheric conditions, but their natural operating frequencies are well suited to operation in most clear-sky atmospheric conditions. Since the SSL frequency and chemical composition of the atmosphere are largely fixed, the issue that adaptive optics strives to solve is atmospheric turbulence.

Adaptive Optics and Atmospheric Turbulence Correction

Atmospheric turbulence results from thermal and density gradients along the laser beam path. These gradients cause the commonly observed effect of twinkling of stars due to changes in the refractive index of the air mass.[44] The understanding of and correction for this phenomenon is the primary focus of adaptive optics. The adaptive optics problem is well understood and adaptive optics correction has been used for a long time on terrestrial telescopes. Adaptive optics hardware is integrated on the ABL platform. Upcoming ABL flight tests will provide an opportunity to demonstrate the maturity of adaptive optics compensation of high power laser beams in a relevant environment.

There is no universal agreement on the readiness of adaptive optics for use on HELs. As one AFRL researcher said of adaptive optics, "we are still in the early stages of development. Adaptive optics may add too much additional cost and complexity to be used on a tactical system, or, with a few breakthroughs, it may be a game changer."[45] Beam control technologies like adaptive optics and AFC are under active investigation by AFRL/VA and AFRL/DE. Their design concept is to reduce distortions as much as possible using AFC, and then minimize the effect of the remaining distortions with adaptive optics. Their goal is to conduct a ½-scale wind-tunnel demonstration sometime in FY 09.[46]

Improvements in adaptive optics algorithms, computer processing capability, and miniaturization of adaptive optics mirror correction actuators are needed to improve adaptive optics performance. At this time, Lockheed Martin engineers do not consider adaptive optics maturity to be a limiting factor for LSF laser beam control. After adaptive optics, optical turret turbulent flow correction and pointing accuracy constitute the majority of the remaining solvable laser power attenuation issues. Active flow control of optical turret turbulent flow is discussed next.

Active Flow Control

Lockheed Martin engineers feel correction of flow instabilities surrounding the optical turret is the most challenging engineering issue in the entire LSF program. The maximum field-of-regard for the JSF HEL is -10° to -90° in elevation and ±180° in azimuth measured from the 12:00 position. The elevation limitations occur because the optical turret is mounted on the bottom of the JSF. Actual LSF laser coverage may be less than the theoretical ±180° in azimuth allowed by the system design due to optical distortion caused by airflow instabilities around the turret. According to Lockheed Martin engineers, even with adaptive optics and active flow

control, turbulent flow aft of the turret may preclude effective use of the laser past approximately ±165°. If flow instabilities cannot be corrected with active flow control, Lockheed Martin engineers anticipate a useable azimuth of approximately ±110°.[47]

There are two broad classes of flow instabilities surrounding the turret; fairly static mach shock waves on the forward part of the turret and highly dynamic turbulent flows on the aft part of the turret. Correction for the optical distortion caused by the shock waves on the forward part of the turret is relatively straightforward.[48] Correction factors for a combination of altitudes, airspeeds, and flight conditions can be derived and stored in a look-up table and applied in real time. Correcting for the highly dynamic turbulent flows on the aft part of the turret is a more challenging problem.

There are three major issues involved with compensating for the optical errors induced by the turbulent flow on the aft part of the optical turret. Those issues include measurement of the instabilities, real or near-real time computation of corrections for the instabilities, and then real or near-real time application of some physical forces to reduce or eliminate the instabilities. According to Lockheed Martin engineers, only actively generated perturbations directed at the flowfield around the turret will be capable of managing the instabilities found there. Other techniques such as fixed vortex generators or suction are well understood and will not be capable of managing the airflow instabilities around the turret.

The reader may ask why there is a difference between adaptive optics correction for atmospheric instability and the turbulent flow problem around the optical turret. Stated another way, can adaptive optics be used to correct for optical turret turbulent flow in the same way that adaptive optics is used to correct for atmospheric instabilities? The answer lies in the dynamic nature of the turbulent flows. The atmospheric turbulence that adaptive optics is compensating

for is correctable by computers deriving corrections within .5 to 1 ms with deformable mirrors operating at about 1 kHz.[49] In contrast, the corrections for turbulent flows will require deformable mirrors operating at 5-10 kHz, an order of magnitude improvement. Furthermore, the stroke length and number of actuators needed to correct for turbulent flows around the turret are approximately 30 microns and much more than 100 actuators.[50] Adaptive optics will be used to correct for any optical distortion remaining after the active flow control system does what it can. However, adaptive optics without active flow control is not capable of compensating for the optical distortions around the optical turret unless dramatic improvements occur in adaptive optics algorithms, processing speed, and adaptive optics actuator capability.

What is the likelihood of continued progress in the science and engineering of active flow control? Researchers point to continued improvement in understanding of fluid dynamics, correction algorithms, and computation as indications of likely improvement in the ability to characterize, understand, and correct turbulent flows. A 2004 statement by AFC researchers said, "…advances in algorithms and the sustained increase in hardware capabilities in recent years permit addressing the instability of essentially nonparallel flows of engineering significance."[51] However, the same research paper pointed to the difficulties in AFC, and how extrapolations of computer processing power in 1976 pointed to projections of AFC solutions in 4-10 years, solutions that had not been achieved 25 years later.[52]

There are however, several efforts currently working the AFC problem. Those efforts include projects by AFRL, the JTO, and DARPA. The AFRL program is focused on low Mach (0.5M and below) corrections for the C-130 and the JTO program is exploring basic AFC science and technology issues. The DARPA program has the most applicability for the LSF project and has demonstrated both AO and AFC in a 1/8 scale wind tunnel, achieving the level of correction

needed for aft quadrant employment of the LSF laser. The DARPA program is currently projected to progress to full-scale wind tunnel testing in the 2009 to 2010 timeframe.[53]

Beam Control and Aero-Optics Technology Outlook Consensus

Lockheed Martin engineers believe adaptive optics and active flow control will be the most challenging and potentially limiting engineering problems in the LSF program. The potential limitations are worth examining for a moment. Currently, USAF fighter aircraft are equipped with missiles that are useable in the forward hemisphere only. Guns on USAF fighter aircraft are employed straight ahead. The vast majority of air-to-ground munitions are also typically restricted to front-hemisphere employment. This perspective on current limitations with the majority of USAF fighter employed ordnance is important because a potential limitation with the LSF laser that only permits operation ±110° of the 12:00 position would largely match current fighter ordnance employment envelopes. The only significant limitation resulting from a ±110° employment limitation would be if the LSF laser was also used in a self-defense capability. The potential limitation on rear hemisphere laser employment would increase the vulnerability of the LSF to threats approaching from the rear hemisphere compared to a LSF that had a laser capable of ±180° employment. However, much like current layered defenses such as chaff, flares, and jamming, the HEL should be viewed as contributing to the overall defensive capability of the LSF as part of a system of systems.[54]

Of the two areas, active flow control is the most dependent on the actual airframe and optical turret being used and will likely not be fully solved until a platform is selected for first fielding of a tactical SSL.

Thus far we have examined the current technical maturity and outlook for bulk and fiber SSLs, power generation and storage, thermal management, and aero-optics. The next chapter

will look at the LSF program as a whole to determine whether structured development programs, sufficient time, and adequate funding exist to field a LSF in 2025.

Chapter 7

Programmatics

Developing the LSF by 2025 will depend on a triad of factors: structured development programs, sufficient time, and adequate funding. This chapter will attempt to answer three questions. First, are there programs in place or planned to bring the HEL and associated subsystems to sufficient technological maturity in time to field a LSF in 2025? Second, is there enough time to mature a SSL and associated subsystems to meet the requirements of the LSF program? Finally, is adequate funding programmed to mature the SSL and its associated subsystems and technologies before the LSF program needs them?

HEL and Associated Subsystems Programs

The table previously shown in Chapter 2 is repeated here to remind the reader of the subsystems and technologies needed to support the LSF SSL.

Table 3. Issues Pertaining to HEL Installation on the JSF

Technology and Programmatics	Effectiveness Limiting
HEL Technical Maturity	HEL Employment Policy
Power Generation	HEL Effects Characterization
Power Storage	HEL Employment Doctrine
Thermal Management	Weather
Adaptive Optics / Active Flow Control	Battlefield Obscurants
LSF Cost and Schedule	

AFRL has implemented a strategic technology investment program called Focused Long Term Challenges (FLTCs). Each FLTC focuses on a specific warfighter capability, and then specifies the technologies required to provide that capability. FLTC 3 - "Dominant Difficult Targets Engagement/Defeat" has a sub-area, Problem 3.5 – "Deliver On-Demand Lethal Effects to Difficult Targets with Ultra-Precision". Under the 3.5.1 Non-Kinetic sub-area reside all of the technologies listed in Table 3.'s first column. The AFRL products corresponding to the Table 3 issues are shown in Table 4.

Table 4. AFRL FLTC Products Enabling LSF Development[55]

Technology and Programmatics	**AFRL FLTC Product**
HEL Technical Maturity	3.5.1.1 Electric Laser & Hybrid (Elec.Chem) Laser
Power Generation	3.5.1.6 Power and Thermal Management for High Energy Laser
Power Storage	3.5.1.6 Power and Thermal Management for High Energy Laser
Thermal Management	3.5.1.6 Power and Thermal Management for High Energy Laser
Adaptive Optics / Active Flow Control	3.5.1.2 Beam Control and Adaptive Optics 3.5.1.3 Flow Control to Mitigate Near-Field Aero-Optic Interference

Each of the AFRL FLTC products describes a detailed program designed to mature the underlying technologies to a Technology Readiness Level (TRL) 5 or 6, which should be sufficient to supply the LSF program with the enabling technologies it will need.[56] It is clear that AFRL has programs to address maturing relevant technologies to support the LSF. The question is whether these programs will mature the technologies in time to support a 2025 flight test program for the LSF.

Time

Lockheed Martin has produced a proposed LSF development roadmap, which would support a 2025 LSF flight test program. Current JSF development cycles are approximately 9 years in duration, from the time pre-design is started until Operational Test and Evaluation (OT&E) activities are complete. For the LSF to complete OT&E activities in 2025, pre-design would need to start in 2016. The LSF development effort would run concurrently with the already planned Block 8 JSF cycle. As of this date, Blocks 6 through 9 requirements are undefined, so accommodation of LSF activities should not disrupt currently planned capabilities development efforts.

Comparison of the previously mentioned FLTC product programs and the proposed LSF development program from Lockheed Martin indicate the enabling technologies from AFRL should be ready in time to support the 2025 LSF flight test program. The only exception to this is in the area of active flow control, FLTC 3.5.1.3, where mitigation of near-field distortion at high speeds will not be ready until 2017-2025. This should not affect the viability of the overall program, only the viability of rear hemisphere employment, and should be a capability that is easily captured in a future LSF spiral development program if necessary.

None of the issues we have explored so far seem to preclude LSF flight-testing in 2025. As we move to the final section on funding, we will uncover the most probable limiting factor in the entire LSF program.

Funding

Development programs for a 100 kW class SSL and the other enabling technologies discussed in this paper are of relatively modest cost compared to the cost of developing a new variant of the JSF. Review of AFRL's FLTCs show all of the FLTC Products shown in Table 4

are largely fully funded through the Future Years Defense Program (FYDP) budget. The largest component of the LSF program cost will be in the development of the LSF itself and the cost of integrating the SSL and enabling technologies in the LSF. According to Lockheed Martin engineers, the LSF will most efficiently be designed as a distinct fourth variant of the JSF, joining the existing USAF CTOL (Conventional Takeoff and Landing), USN CV (Carrier Variant), and USMC STOVL (Short Takeoff Vertical Landing) versions. Current design studies envision modifying the USAF CTOL version, removing an existing fuel bladder and replacing it with the HEL and associated subsystems.[57]

It is difficult to estimate the cost of modifying the CTOL variant into the LSF and integrating the SSL and associated subsystems into it without performing a comprehensive analysis of the program; conversations with Lockheed Martin engineers put the cost estimate in the range of $100s of millions of dollars. That would be for the LSF integration effort only and not include the cost of individual LSF airframes. The price for a single squadron of 24 LSFs would be over $1 billion in 2002 dollars, assuming a unit cost of $44.5 million based on Government Accountability Office data. The $44.5 million dollar unit cost is conservative for the LSF since it applies to the current CTOL version of the JSF.[58] The estimates for the LSF integration program and the cost of the LSF's themselves are rough order of magnitude estimates and are mentioned to make the point that a decision to develop and procure a LSF is a decision that will require a major USAF commitment. In the current environment of constrained budgets, this major commitment would likely come at the expense of other ongoing or proposed USAF programs.

Chapter 8

Conclusion and Further Questions for Consideration

This paper considered whether the technical maturity of HELs and necessary supporting systems would permit fielding of a HEL equipped F-35 Joint Strike Fighter (JSF) in the 2025 timeframe. To answer this question, three topics were explored. First, would HELs be sufficiently technically mature to permit installation on a fighter platform? Second, would the key supporting systems, to include power generation and storage, thermal management, and beam conditioning and control, be sufficiently technically mature for installation on a fighter platform? Finally, are the development schedules and funding for the HEL, key supporting systems, and the JSF synchronized to support a 2025 fielding?

Based on the evidence examined throughout this paper, it seems clear that all of the technologies needed to produce a LSF will be ready by 2025.[59] As a further indication of the increasing maturity of laser technologies, the Pentagon's Acquisition, Technology, and Logistics director recently tasked the Defense Science Board to form a task force to review ongoing Department of Defense (DoD) directed energy (DE) efforts. The director noted the rapid advancement of DE technologies and indicated that DE systems may be sufficiently mature to contemplate integrating them into operational forces. The goals for the task force are to determine whether any current DoD DE programs are duplicative, whether any DE areas are unexplored, and to also propose roadmaps to integrate DE into operational forces; their report is

due by the end of May 2007.[60] Since technology does not seem to be the limiting factor for fielding the LSF in 2025, are there any other issues that could have an impact? It seems clear that the key issues that could prevent the LSF from becoming reality are not technical, but rather are questions of institutional resolve and availability of funding.

Determining the answers to these last two questions is difficult. In the end, availability of funding is a function of institutional resolve. If the capability provided by the LSF is sufficiently compelling, the USAF could choose to reprogram funds to support the LSF effort. The question then is whether there is a compelling rationale for procuring the LSF. Answering whether the LSF's capability is compelling enough to warrant acquisition by the USAF is beyond the scope of this paper. However, it is probably useful to briefly discuss some of the issues that need to be studied to answer that question.

Integrated air defense systems are becoming more capable with time; advanced acquisition and tracking radars and larger employment ranges make these systems increasingly lethal. The HEL on the LSF will not provide a standoff weapon capability against a modern surface-to-air missile (SAM) employment site, or even legacy systems such as the SA-2 due to HEL employment ranges being well inside most SAM employment ranges.[61] Given that employment constraint, the LSF may only possess a defensive capability against airborne SAMs.

In the air-to-air role, the HEL will not be a replacement for the AIM-9 or the gun when the LSF is in a turning engagement, since the pilot will most likely have the top of the LSF towards the adversary, thereby shielding the bottom mounted optical turret. This limitation does not preclude use of the HEL at longer ranges or in non-turning engagements. It does mean the HEL will provide a complementary capability to existing fighter air-to-air weapons, but not replace them.[62] Of course, one might ask whether a HEL equipped fighter will have a need to

engage in a turning fight. HEL technology may change tactics as much as beyond visual range ordnance has changed the way pilots think about and execute the air-to-air fight.

The counter-cruise missile mission may be one of the most compelling reasons to acquire an airborne HEL capability. This mission requires a deep magazine with long on-station times. The LSF would certainly possess a deep magazine. Long on-station times would be a function of the LSF's inherent air refueling capability and pilot endurance. The desire for long on-station times does prompt the question of whether the counter-cruise missile mission is best performed by a LSF, or would another platform have the size and endurance to more effectively execute this mission.

The USAF is embarking on two future strike vehicle programs, the first fielding in 2018 and the second in 2030. These strike vehicles are currently planned to be long range, stealthy platforms with long endurance [63]. Furthermore, their size compared to the LSF may reduce the overall risk of a HEL integration program by providing more volume and weight capacity than the LSF. If maturing HEL technology by 2025 becomes problematic, the 2030 long-range strike platform may offer an alternative vehicle for the USAF's first "tactical" HEL capability. The 2030 long-range strike platform may offer additional advantages compared to the LSF: five more years available to mature the enabling technologies, greater weight and volume available for the HEL, and finally a clean sheet of paper to design HEL capability in from the beginning.

There are two issues worth exploring when comparing the LSF concept to the long-range strike platform, power and employment envelope. First, the advantage of having the STOVL shaft available to provide power for the HEL should not be underestimated. Designing an engine for use in the long-range strike platform that can provide the power needed for HEL operation is potentially very costly. Second, the long-range strike vehicle is envisioned to operate at high

altitudes and high speeds. For air-to-ground scenarios, high altitude flight will decrease the operational range of the HEL due to having to go through more atmosphere on the way to the target. High-speed flight also presents some challenges with regards to correcting flow field perturbations as previously discussed in the section on AFC. If the long-range strike platform is optimized for high-altitude, high-speed flight, it may inherit commensurate compromises in its operational effectiveness.[64]

In conclusion, the limitations for having LSF capability in the USAF inventory by 2025 are ultimately funding and the operational capability provided by a LSF, not the technological maturity of HELs and key supporting systems. While challenging, the technology maturation needed to provide HEL capability on the LSF by 2025 seems achievable. The essential next steps will be to first answer the question of whether the unique and complimentary capabilities provided by a HEL on a tactical sized platform are needed, determining if adequate funding is available, and finally deciding whether the LSF should be a greater priority for funding than other ongoing or proposed programs.

Appendix A

Laser Fundamentals

There are many sources available to give the reader an understanding of the physics behind laser operation, the different types of lasers, and the capabilities and limitations that lasers possess. Some of those resources are listed below:

Table 5. Sources for Learning About Lasers

Source	What is useful for?
Beason, Doug. *The E-Bomb*, Cambridge, MA, Da Capo Press, 2005.	General overview of directed energy technologies and their uses
Air Force Institute of Technology - Laser Weapon Systems Short Course	From the basics to the fundamental physics behind laser operation
Mansfield, Robb P. "High Energy Solid State and Free Electron Laser Systems in Tactical Aviation." Master's thesis, Naval Postgraduate School, 2005.	The physics behind laser operation
Kalfoutzos, Aristeidis. "Free Electron and Solid State Lasers Development for Naval Directed Energy." Master's thesis, Naval Postgraduate School, December 2002	The physics behind laser operation
http://www.colorado.edu/physics/2000/lasers	"Lasers for Dummies" – a very good pictorial and textual explanation about how lasers work

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8. Government Accountability Office. *Department of Defense’s Assessment Addresses Congressional Concerns but Lacks Detail on High Energy Laser Transition Plans* GAO Report 05-933R (Washington, D.C.: Government Accountability Office, 28 July 2005)

9. Government Accountability Office, *Joint Strike Fighter – DoD Plans to Enter Production before Testing Demonstrates Acceptable Performance*, GAO Report 06-356, (Washington D.C.: Government Accountability Office, 2 March 2006)

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14. Lay, Christopher, Miller, Charles, Horowitz, Michael. *Operational Concepts for Directed Energy Weapons-Implications for Future Warfare*. SAIC Report 04-6972&SAC. Washington, D.C.: Science Applications International Corporation, Strategic Assessment Center, February 2004

15. Liu, Liping, Zhou, Yi, Kong, Fanting, Chen, Y.C., Kotlik, K. Lee. “Phase Locking in a Fiber Laser Array With Varying Path Lengths.” *Applied Physics Letters* Vol. 85 no. 21 (November 2004). 4837-9.

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[11] Robb P. Mansfield, “Solid State Laser Systems,” 12
[12] Ibid., 43-44.
[13] Andy Motes, et al., “Laser Technology Assessment,” 11, 13, 17
[14] Andy Motes, et al., “Fiber Laser Technology Assessment,” 19-20
[15] Tom Burris, email message to author, 23 February, 2007
[16] Andy Motes, Sean Ross, Gerald Moore, Erik Bochove, Anthony Sanchez, Tim Newell, Justin Spring, William Thompson, “High Power Fiber Laser Tutorial & Technology Assessment,” (Kirtland AFB, NM: Air Force Research Laboratory, April 2006), 6 and Dr. Lawrence E. Grimes AFRL/DETA, email message to author, 21 January 2007
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[26] Andy Motes, et al., “Fiber Laser Technology Assessment,” 19-20
[27] Dr. Lawrence E. Grimes AFRL/DETA, email message to author, 21 January 2007
[28] It should be noted that the LSF will require more design than just dropping a HEL and some generators and thermal management equipment into an empty STOVL bay. The LSF will be a distinct variant of the JSF, just as the STOVL and CTOL (Conventional Takeoff and Landing) versions are distinct from each other.
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[30] Tom Burris, email message to author, 3 November, 2006
[31] Tom Burris, email message to author, 23 February, 2007
[32] Duty cycle is the percentage of operating time compared to the total available time. A motor that could only run 30 minutes out of every hour would have a duty cycle of 50%.
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[38] Robb P. Mansfield, “Solid State Laser Systems,” 16
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